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Using Life-Cycle Analysis to Estimate Economic Performance

B. R. Allenby
K. Blades
T. J. Gilmartin

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Lawrence Livermore National Laboratory

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Braden R. Allenby
Karen Blades
Thomas J. Gilmartin

Lawrence Livermore National Laboratory
PO Box 808
Livermore, California 94550

Industrial ecology[1] is the scientific, multidisciplinary study of industrial and economic systems and their linkages with natural systems. Industrial ecology provides the understanding, the tools, and the technologies for achieving sustainable development.

Lawrence Livermore National Laboratory is engaged in a major research effort in industrial ecology including such areas as energy supply and use, novel and environmentally preferable materials, and environmentally conscious manufacturing and transportation technologies as well as computational modeling to understand and mitigate local, regional, and global environmental effects. At Livermore we are drawing on academic and private industry expertise to support a national effort to define a broad agenda for U.S. research in industrial ecology.

LIFE-CYCLE ASSESSMENT

One of the principal tools of industrial ecology is life-cycle assessment which intends to improve overall economic efficiency and to minimize negative environmental impacts of products, processes, and facilities. In the following paper we will describe a general methodology for environmentally responsible assessment of these activities; we will discuss some of the underlying considerations for this assessment which are accessible by rigorous quantitative analysis; and we will then propose an overall economic performance metric, $Q_{V/C}$, which puts both environmental and economic considerations on a common basis. Finally, we will introduce some considerations involved in the application of this approach as a guide to environmentally sound design and management.

Environmentally Responsible Assessment Matrix

A suitable environmentally responsible assessment system is thought to have the following characteristics:

- encompasses all stages of operations and all relevant economic and environmental concerns
- is simple enough to permit relatively quick, meaningful, and inexpensive assessments to be made
- is usable by and reasonably consistent across different assessment teams
- lends itself to direct comparisons among alternatives.

Experience demonstrates that life-cycle assessments for complex products, processes, or facilities are most effective when done in modest depth and in a qualitative manner by a DfE (design for environment) specialist and team of experts knowledgeable about the activities involved. The environmentally responsible assessment system devised by Graedel and Allenby[2,3] is straightforward and demonstrated to meet the criteria given above. This assessment system as applied to a product will be used as the basic framework for defining $Q_{V/C}$.

The central feature of the assessment system is a 5x5 matrix, one axis of which is environmental concerns relating to material and energy uses and residues, the other is the five life-cycle stages, namely, initial extraction and preparation of the material resources, manufacturing of the product, packaging and distribution, use, and recycle or disposal.

With the guidance of, say, DfE checklists, the assessor studies the environmental impact of the different activities and assigns to each element, R_{SC}, of the matrix a rating from 0 (*highest environmental impact, most negative evaluation*) to 4 (*lowest environmental impact, excellent evaluation*). Recommendations which will improve the element score are given for each matrix element. The overall environmentally responsible rating, R_{LCA}, is the sum of the matrix element values yielding a maximum possible rating of 100.

$$R_{LCA} = \Sigma R_{SC},$$

where s and c refer to the five each life-cycle stages and environmental concerns, respectively, in the assessment matrix. This rating is qualitative and practical, and, if used consistently, is suitable for identifying and ranking the highest potential improvements for the design.

LIFE-CYCLE ANALYSIS

Although the environmentally responsible assessment system produces a quantitative evaluation, it does not provide a measure for estimating the economic performance of design alternatives. In each of the life-cycle stages, however, there are material, energy, and capital considerations, each of which is quantifiable in design terms and reducible to economic terms. We will consider each of these in turn.

Mass Balance

Mass balance is of critical importance in process design if either the material used is of great value or of significant hazard, although minimizing the amount of material used and the amount of residue that must be dealt with will always be of some benefit environmentally and potentially economically. Accounting for all mass flows will identify material inefficiencies, wastes, "leaks" in the processes, and opportunities for recycling to decrease the initial resource need and reduce the overall material use. Mass balance is also readily accountable in monetary terms, namely the cost of the resources, the benefits for recycling residues to decrease resource costs, and the cost for disposal. We will discuss the "risk" cost associated with environmental damage below under capital costs and risks.

Energy Balance

Energy use is very analogous to material use in that a well designed life cycle minimizes the energy use in both production and product use, indeed in all life cycle stages, and minimizes waste and the compensatory costs, for example, having to cool the plant because the process emits heat. Like materials, energy used in production is readily costable simply as the bill for the energy resources used. However, it is important to be able to segregate the energy which is necessary for the production process and that which is plant related. In addition the energy costs associated with the other life-cycle stages must be accounted. Additionally there are energy costs associated with residues and potential environmental effects with longer term risks which we will account as capital risks and costs.

Capital and Risk

Finally, there are the costs and risks associated with labor, capital, and capital risks which threaten the market value of the company and of its products. These items are on the one hand direct costs required for production, and on the other hand the accountable liabilities for risks to the employees, the plant, the consumers, and the environment. The risk costs have traditionally been accounted actuarially and paid as insurance applied relatively indiscriminately to both careless and careful clients. In current times, insurance has been replaced by risk management or self insurance which strongly motivates avoidance of vulnerability to short and long term risks. This practice is generating both much greater interest in environmental science and environmental management, and an increasing ability to accurately estimate the cost of potential environmental threats, both gradual and critical.

ECONOMIC PERFORMANCE MEASURE: $Q_{V/C}$

With these considerations in mind, we propose an economic performance measure, $Q_{V/C}$, which is the value, V, of the finished product or the value added by a process or service, divided by the sum of the costs, both the direct costs, C^D, normally associated with production (material, energy, labor, and capital) and the external costs, C^E, (material and energy residues; environmental, compensatory, and product energy uses, and all of the costs to indemnify or mitigate environmental risks), often referred to as "externalities".

$$Q_{V/C} = \Sigma V_S \, / (\Sigma C^{D}_{SC} + \Sigma C^{E}_{SC}),$$

where s and c refer again to the five life-cycle stages and the five environmental concerns, respectively, associated with the life-cycle assessment matrix. This economic performance measure "internalizes the externalities", a key objective of industrial ecology.

Use of $Q_{V/C}$

The use of $Q_{V/C}$ as a single parameter for optimization of complex activities or individual steps in the life cycle is the subject of a longer discussion which we will engage in the presentation of this paper. Suffice it to say that the objective for the designer or the company manager is to maximize $Q_{V/C}$; the objective for the consumer is to verify that the product or service provider is acting in a manner that will achieve the product and environmental quality indicated by a high $Q_{V/C}$. The realization of this consumer knowledge and responsibility is the purpose of enlightened policies and practices which are extremely important and interesting to study, but are beyond the scope of this paper. We wish only to propose that $Q_{V/C}$ reduces very complex considerations to a single parameter that relates directly to the bottom line of the company, to the interests of the consumer, and to the environmental improvement interests of both.

Conclusion

The actual implementation of environmental improvements while maintaining economic growth is the ultimate goal of industrial ecology. The decisions and actions taken by corporations will be based on a variety of trade-offs. Economic performance metrics which internalize environmental considerations for the life cycle of products, processes, and facilities will help in making balanced choices, and ultimately in evolving a sustainable economy.

[1]Graedel, T. E. and B. R. Allenby, Industrial Ecology, 1995 by AT&T (Prentice-Hall, Englewood Cliffs, New Jersey 07632).

[2]Graedel, T. E., B. R. Allenby, and P. R. Comrie, "Matrix approaches to Abridged Life-Cycle assessment," Environmental Science and Technology, Vol. 29, 1995; pp. 134A-139A.

[3]Graedel, T. E. and B. R. Allenby, 1994, "The Environmentally Responsible Facility Matrix System," Third Annual National Academy of Engineering, Industrial Ecology Workshop.

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